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A wideband apodized FBG dispersion compensator in long haul WDM systems

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This work introduces a new design of wideband dispersion-compensation (WBDC) apodized chirped fiber Bragg grating (ACFBG) unit that covers the entire C band. Its length is chosen to be with the maximum apodized fabricated length of 30 cm that grants a dispersion of -66.7 ps/nm/km. This design is compared with multi-narrow band ACFBG in a long haul wavelength division multiplexing system of 3000 km at different bit rates. The obtained results reveal that the multi-narrow band system is better than WBDC system at low bit rate (i.e. 10 Gbps) achieving a quality factor 30% of its maximum value at mid distance. However, WBDC transmits signals with higher bit rates as 20 Gbps for 1800 km and 40 Gbps for 1000 km, while multi-narrow band system cannot transmit signals with higher bit rates at all. Moreover, generally multi-narrow band units have a multiple FBG spaced from each other, which requires high temperature stability. In the other hand, WBDC CFBG does not need a temperature controller (i.e. no internal gaps between channels).

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1. Introduction

The Severe need for very high data transfer rates is forcing most telecommunication companies nowadays to use optical fiber links. In order to achieve high efficient long haul fiber links, wavelength division multiplexing (WDM) is introduced [1, 2]. Dispersion is a main limiting factor in designing long-haul optical links [3]. Several techniques have achieved effective dispersion compensation (DC). The wide commonly used techniques are the dispersion-compensation fiber (DCF) [4, 5], and the chirped fiber Bragg grating (CFBG) [5, 6]. Although DCF is a wide band unit, but CFBG outperforms it from many faces [5, 7].

CFBG is an effective dispersion-compensation unit due to its compactness, passiveness, low cost, low insertion loss, and lack of nonlinear effects compared to DCF [5]. Apodization is a decisive procedure to improve the dispersion performance of CFBG [6]. The aim of apodization functions is to reduce reflectivity of sidelobes and group delay ripples (GDR) and to smooth the reflection spectrum [6, 8, 9]. Applying an apodization function to the CFBG profile performs the apodized chirped fiber Bragg grating (ACFBG) unit.

Before 2005, most of literatures uses CFBG as a narrow band unit covering a maximum full width half maximum (FWHM) of 2 nm of C-Band [10, 11, 12]. In order to expand the used bandwidth, researchers used multi CFBG as a multi-narrow band dispersion compensation unit [13, 14].

Y. Chen et al. designed eight narrow band FBGs each with a maximum FWHM of 0.45 nm [13]. The resultant dispersion for each grating is ~ - 2.65 ns/nm. This constructs a system of 8×10 Gbps with BER of 10^{-12} at launched power of +3 dBm for a total length of 2015 km. H. Li et al. used a phase sampled CFBG to obtain a 45 narrow band (100 GHz spacing) to cover the full C band with dispersion of -1020 ps/nm [14]. Although the phase sampled CFBG is not imported in a system, but its given dispersion can used for a single mode fiber (SMF) cable of length 60 km. However, high temperature stability is required in multi-narrow band scenarios. Otherwise, narrow band channel spacing is moving across the wavelengths as the temperature increases and destroy the transmitted signals. Moreover, in a system of signals with higher bit rate more than 10 Gbps (i.e. 40 Gbps or more) cannot be transmitted.

Alternatively, in [15], a wide band dispersion compensating CFBG unit was designed to have a FWHM of 35 nm but with length of 15 cm. This length delivers a dispersion of -33.6 ps/nm which means that it can compensate only 2 km for a standard SMF cable (i.e. dispersion +17 ps/nm/km). In [16], a new fabrication technique extended the max fabricated ACFBG length to 30 cm.

In this work, a new design for a wide band DC CFBG unit is introduced with the maximum fabricated length. This design compensates the dispersion of a SMF cable length of 3.92 km/span and is imported in a system to cover a long haul of 3000 km. This wide band system is compared with other ones importing multi-narrow band CFBG covering the same distance.

The remainder of this paper is organized as follows. Section 2 describes the mathematical model and theory used in this study. The two systems are described and compare in Sec. 3. The obtained results are presented and discussed in Sec. 4. This is followed by the main conclusions in Sec. 5.

2. Mathematical model

2.1 CFBG profile

In a CFBG, the modulation of induced index varies along the grating length periodically. As the grating period varies along the axis, the different wavelengths are reflected by different parts of the grating. The fast wavelengths of the pulse (λ_S) reflect from the shortest grating period in the chirp taking the longest time while the slow wavelengths (λ_L) reflect from the longest one taking the shortest time, resulting in a compression in the input pulse. The range of reflected wavelengths is provided by [5, 17]

$$\Delta\lambda_{Chirp} = 2n_{eff}(\Lambda_L - \Lambda_S) = 2n_{eff}\Delta\Lambda_{Chirp} \quad (1)$$

where $\Delta\lambda_{chirp}$ is difference between longest wavelength (λ_L) and shortest wavelength (λ_S), Λ_L is the longest grating period and Λ_S is the shortest grating period and n_{eff} is the effective refractive index. Then, the delay time $\tau(\lambda)$ for light reflected of a grating is given by [18]

$$\tau(\lambda) = \frac{(\lambda-\lambda_S)}{(\lambda_L-\lambda_S)}\frac{2n_{eff}L_g}{C} \quad (\lambda_S \le \lambda \le \lambda_L) \quad (2)$$

where C is light speed in space and L_g is the grating length. The rate of change of this delay $\tau(\lambda)$ with wavelength gives the dispersion $D(\lambda)$ according to [18]

$$D(\lambda) = \frac{d}{d\lambda}\left(\tau(\lambda)\right) = \frac{1}{(\lambda_L-\lambda_S)}\frac{2n_{eff}L_g}{C} \quad (\lambda_S \le \lambda \le \lambda_L) \quad (3)$$

Chirping profiles may be linear, square root, and cubic root profiles. However, the linear chirping profile is the optimum choice for dispersion compensation purposes [5]. In this work, we use the linear chirp profile, which is given by where E_o is a grating period at the center wavelength and Δ is total chirp of linear grating.

$$\Lambda(x) = \Lambda_o - \left(\left(x - \frac{L_g}{2}\right)/L_g\right) \times \Delta \quad (4)$$

2.2 Apodization profile

The apodization function aims to reduce the side lobe level in the reflectivity response and the group delay response ripples. Although there are different apodization functions, we have chosen the tanh apodization function because it offers high bandwidth, reflectivity, side lobe suppression ratio (SLSR), and low GDR among other apodization function [8, 9, 15]. The tanh function (y) can be represented by:

$$y = 1 + \tanh\left(ax/L_g\right)\tanh\left[a\left((L_g - x)/L_g\right)\right] - tanh^2(a/2) \quad (5)$$

where a is the apodization strength.

3. System Model

3.1 Wideband CFBG unit design

The design parameters for wideband CFBG unit are set as Δn is 4×10^{-4}, Δ is 0.1027 nm/mm, grating length L_g is 30 cm and the number of segments N is 200 [15]. An apodization strength for the tanh function is chosen as a = 6 that achieves the wide band requirements [6, 15, 16].

3.2 Multi-narrow band CFBG unit design

For multi narrow-CFBG unit, we use 16 CFBG units each with Δn is 4×10^{-4}, the total chirp of the linear grating is 0.001 nm/mm [7], grating length L_g is 30 cm, the same apodization function (tanh) with the same strength and segment number are used.

These parameters are then applied on the mathematical model introduced in Sec. 2 and coupled mode theory is used to provide the reflectivity analysis. Figure1 shows the simulated reflectivity spectrum for both wideband and multi-narrow CFBG units that cover a total effective FWHM of 35 nm. Finally, the system is established using system simulator to test these designs.

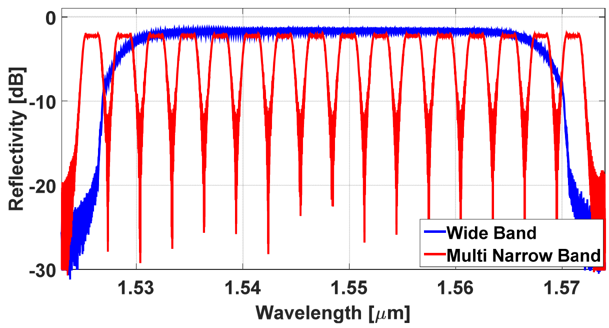


Fig. 1 Effective FWHM in both cases (i.e. wide band & multi-narrow band).

3.3 Wideband and multi-narrow band CFBG system structure

For both systems, the common system structure parameters and specifications are according to Table 1 [19, 20, 21].

Table 1. System parameters and specifications

Block	Parameter	Value	Unit
MUX DEMUX	Insertion loss	2.5	dB
	Channel center accuracy	± 1.25	GHz
	Channel spacing	100	GHz
SMF	Dispersion	+17	ps/nm/km
	Attenuation	0.2	dB/km
EDFA	Gain	20	dB
	Noise figure	4	dB

We design the long haul system of total length 3000 km. As shown in Fig. 2, after modulating each signal using NRZ Mach–Zehnder modulator, a 32 port WDM is multiplexed with 32×1 MUX. The wideband dispersion compensation (WBDC) unit is inserted as post-compensation (i.e. WBCFBG unit after the SMF). The dispersion of WBDC CFBG is - 66.7 ps/nm/km, which compensates a SMF cable of length 3.92 km.

Then, a repeated factor M is chosen such that a total fiber length of 100 km is reached per each span. After each M loops, an erbium doped fiber amplifier (EDFA) is added for N loops. After demultiplexing using 1×32 DEMUX, a random channel is attached to the BER analyzer.

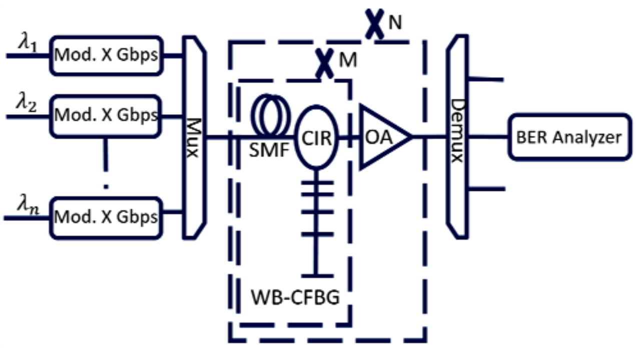


Fig. 2. WBDC CFBG system structure, CIR is a circulator.

As shown in Fig. 3, we build a system to compare it with the previously designed system. After modulating each signal, a 32 port WDM is multiplexed with 32×1 MUX. The multi-narrow band DC (MNBDC) unit is inserted as post-compensation (i.e. MNBCFBG unit after the SMF). After each 100 km SMF, a 16-port power splitter is inserted, followed by 16 MNBDC CFBG units each is responsible for 2.2 nm at different parts of the C band as shown in Fig. 1. This constructs a total of 35 nm FWHM with small gabs between them for signal separation.

After the 16-port power combiner, an EDFA is added for N spans. After demultiplexing using 1×32 DEMUX, a random channel is attached to the BER analyzer.

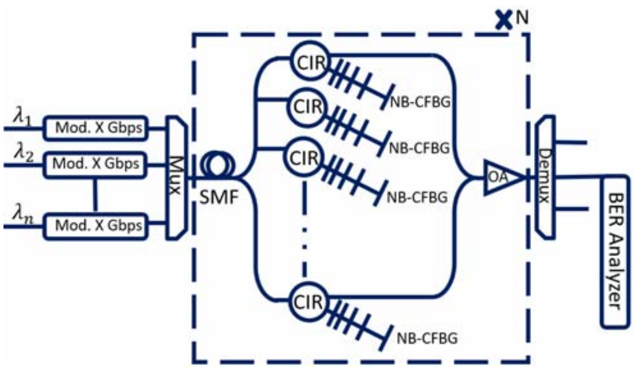
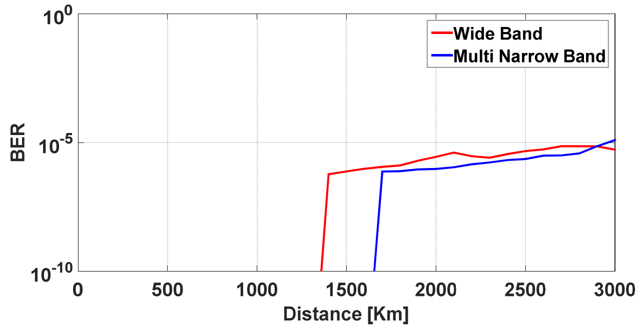


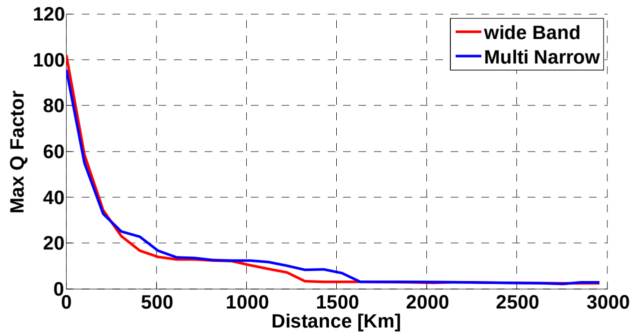
Fig. 3. Multi-narrow CFBG system structure.

4. Results and discussion

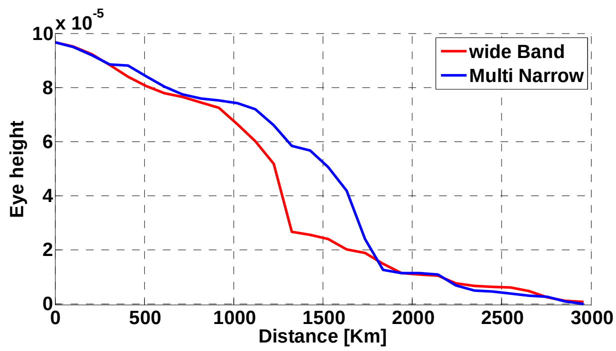
Figure 4 shows that, both wide band and multi-narrow systems are able to transmit a bit rate (BR) of 10 Gbps signals for 3000 km. The multi-narrow system shows lower BER, higher quality factor and higher eye height (eye opening of the eye diagram) than the wide band system. This is because using a circulator and CFBG without following them by an optical amplifier degrades the signal quality and that is the case of wide band CFBG.



a) BER for different distance at BR=10 Gbps



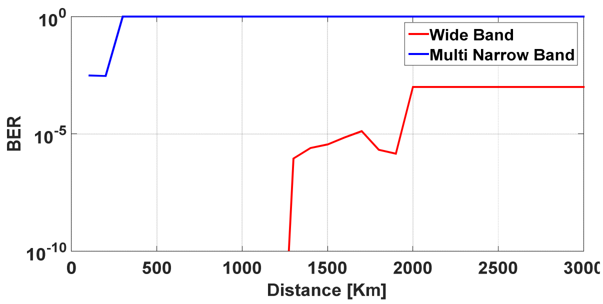
b) Q- factor for different distance at BR=10 Gbps.



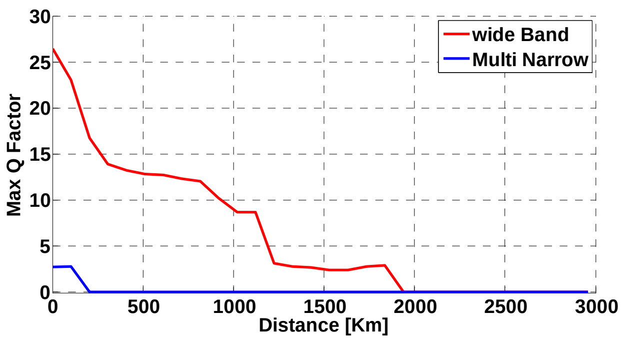
c) Eye height for different distance at BR=10 Gbps.

Fig. 4. Effect of (a) BER, (b) quality factor and (c) eye height for variable distance at bit rate= 10 Gbps.

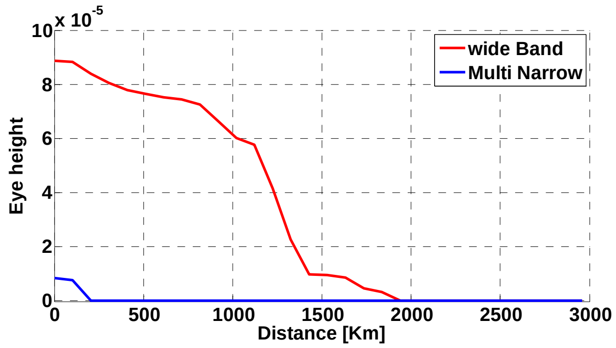
Wide band systems are able to transmit the 20 Gbps signals for 1300 km as depicted from Fig. 5, with high quality factor and then it continues to 2000 km with a decreased quality factor. At 1300 km, the quality factor is 8.6, BER is 10^{-18} and eye height is 5×10^{-5}. While the multi-narrow system transmits signals to 300 km only with a very low quality factor.



(a) BER for different distance at BR=20 Gbps.



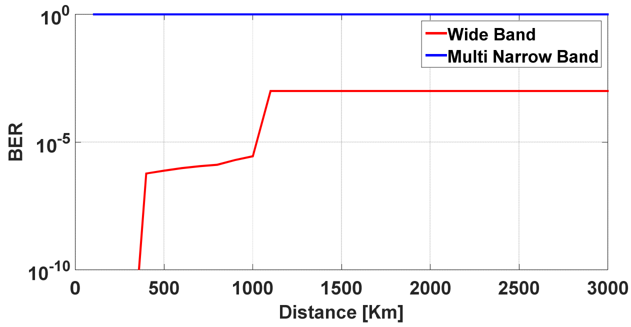
(b)Q- factor for different distance at BR=20 Gbps.



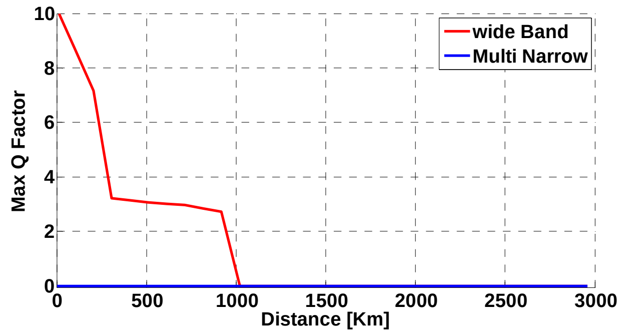
(c) Eye height for different distance at BR=20 Gbps.

Fig.5. Effect of (a) BER, (b) quality factor and (c) eye height for variable distance at bit rate= 20 Gbps.

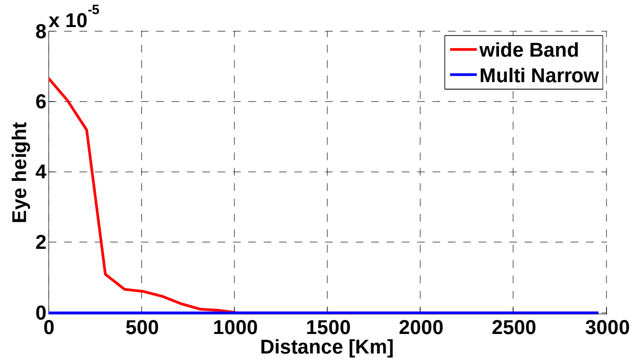
The procedure is repeated for 40 Gbps and the obtained results are displayed in Fig. 6 which shows that wide band systems are able to transmit the 40 Gbps signals for 1000 km with a quality factor of 3, where the BER is 10^{-3} and the eye height is 10^{-5}. The multi-narrow system is unable to transmit any signal at all at this bit rate.



(a) BER for different distance at BR=40 Gbps.



(b) Q- factor for different distance at BR=40 Gbps.



(c) Eye height for different distance at BR=40 Gbps.

Fig.6. Effect of (a) BER, (b) quality factor and (c) eye height for variable distance at bit rate= 40 Gbps.

5. Conclusion

In this paper, a new WBDC CFBG design is proposed. This design is based on the latest CFBG fabrication technology that allows ACFBG with lengths up to 30 cm. In order to show the advantages of this design, we have built two long haul systems. One imports the proposed design and the other is using the old scenario of multi-narrow band CFBG. The performance of both systems for a long haul of 3000 km is compared at different bit rates: 10, 20 and 40 Gbps.

The obtained results show that the multi-narrow band scenario is slightly better at 10 Gbps but it cannot transmit signals with higher bit rate. Moreover, generally multi-narrow band scenarios have a FBG channel spacing, which requires high temperature stability. Otherwise, the channel spacing is moving across the wavelengths as the temperature increases causing signals distraction. On the other hand, WBDC CFBG can easily transmit 20 and 40 Gbps and does not need a temperature controller (i.e. no internal gaps between channels). Instead, only the first channel is affected by temperature shift. The wideband CFBG suffers until now a fabrication problem that prevents designing single WBDC for each span.

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